INTERNATIONAL JOURNAL OF ADVANCE RESEARCH, IDEAS AND INNOVATIONS IN TECHNOLOGY

ISSN: 2454-132X
Impact Factor: 6.078
(Volume 10, Issue 5 - V10I5-1166)
Available online at: https://www.ijariit.com

A Systematic Review of Renewable Power Supply Systems

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ABSTRACT

The present paper dwells on the development and significance of power supply system's progress, relative mainly to their renewable systems of energy sources incorporation. Old electricity distribution systems which have relied on fossil fuel sources of energy supply for many years have numerous drawbacks. Even with winding and extensive development of the 21st-century global economies, outdated forms of electricity supply and the commercial systems they incorporate have their share of disadvantages as they are insensitive to changes in power circuits: Such geometric and technological changes have stalled every so often and the locational logic of control systems and regulatory organs has often rendered uncoordinated the interconnection of grids and electric infrastructure Therefore high voltage DC transmission systems came to the rescue.

This paper addressed solar, wind and hydropower systems among others as captured within the development of new technologies in energy. Even with this remarkable growth in the deployment of renewable energy resources among countries, changing these resources into their grid systems is still a challenge due to intermittency or non-alignment between demand-side response obligations and supply-side response. However, new solutions to such challenges in smart grid technologies include demand responses, storage capacity for electricity, and improved management of electricity distribution.

Keywords: *Power supply, renewable energy, power management, grid management, sustainability*

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1. INTRODUCTION

1.1 Definition and importance of smart grids

Before understanding what a smart grid is, let's understand what an electrical grid is."An electrical grid is an interconnected network for delivering electricity from producers to consumers. It consists of generating stations that produce electrical power, high-voltage transmission lines that carry power from distant sources to demand centres and distribution lines that connect individual customers." (Zohuri et al. #)

The grid used previously had many problems like:

It led to the emission of CO_2 and other greenhouse gasses which contribute to global warming.

It uses fossil fuels like coal and non-renewable energies like nuclear energy for energy.

It had a higher risk of overheating.

It had a distribution loss.

Voltage fluctuations.

"A smart grid is an upgraded version of the electricity grid that includes various advanced technologies to improve the reliability, efficiency, and security of the power grid. These include two-way communication, automation, and advanced metering infrastructure (AMI)." (EPE consulting 14)

“A smart grid is an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users. Smart grids co-ordinate the needs and capabilities of all generators, grid operators, end users and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimising costs and environmental impacts while maximising system reliability, resilience, flexibility and stability.” (International Energy Agency)

The smart grid solves some of the problems shown by the conventional grid. Which we will see in the upcoming section. The importance of the smart grid can be summarized in some key points-

1.2 Overview of renewable energy sources

According to the Renewable Energy Statistics 2024 report by IRENA:

Global Capacity: "As of 2023, the global renewable power generation capacity reached a total of 3,870 gigawatts (GW). Renewables accounted for 86% of new capacity additions" (International Renewable Energy Agency)

Solar Energy: "Solar power continues to dominate the renewable energy sector, accounting for 73% of the capacity growth in 2023. The global solar capacity reached 1,419 GW, with major contributions from China, which added 216.9 GW alone". (International Renewable Energy Agency)

Wind Energy: "Wind power also saw substantial growth, increasing by 13% to a total capacity of 1,017 GW by the end of 2023. The United States and China were the leading countries in wind energy expansion". (International Renewable Energy Agency)

Hydropower: "Hydropower remains a significant renewable energy source, with a total capacity of 1,270 GW. Although the expansion was lower than in previous years, countries like Australia, China, Colombia, and Nigeria added more than 0.5 GW each". (International Renewable Energy Agency)

Bioenergy: "Bioenergy experienced a slower growth rate, with a 3% increase, adding 4.4 GW in 2023. Significant contributions came from China, Japan, Brazil, and Uruguay". (International Renewable Energy Agency)

Geothermal Energy: "Geothermal energy had a modest increase, adding 193 MW, primarily led by developments in Indonesia". (International Renewable Energy Agency)

Off-Grid Renewable Energy: "Off-grid renewable energy capacity grew by 4.6%, reaching 12.7 GW. This growth was largely driven by off-grid solar energy, which reached 5 GW by the end of 2023". (International Renewable Energy Agency)

Significance of integrating renewable energy with smart grids

“Smart grid technology shows us a solution for improved electric energy generation as well as an efficient means for transmitting and distributing this electricity.”- (Kataray et al. #)

“It is simpler to set up and holds up less space than traditional grids due to its versatility.”- (Kataray et al. 2023)

It helps the environment as the use of non-renewable sources is reduced.

Improved Reliability and Stability: By integrating renewable resources, smart grids can better manage fluctuations in energy supply and demand, enhancing the reliability and stability of the power grid.

By integrating renewable resources cost is reduced.

With the integration of renewable sources of energy, fossil fuels are much less used thus decreasing the emission of greenhouse gasses.

1.3 History of Smart Grids

“Commercialization of electric power began early in the 21st century. With the light bulb revolution and the promise of the electric motor, demand for electric power exploded, sparking the rapid development of an effective distribution system. At first, small utility companies provided power to local industrial plants and private communities. Some larger businesses even generated their power. Seeking greater efficiency and distribution, utility companies pooled their resources, sharing transmission lines and quickly forming electrical networks called grids. George Westinghouse boosted the industry with his hydroelectric power plant in Niagara Falls. He was the first to provide power over long distances, extending the range of power plant positioning. He also proved electricity to be the most effective form of power transmission. As the utility business expanded, local grids grew increasingly interconnected, eventually forming the three national grids that provide power to nearly every denizen of the continental US. The Eastern Interconnect, the Western Interconnect, and the Texas Interconnect are linked themselves and form what we refer to as the national power grid. Technological improvements of the power system largely raised in the 51s and 61s, post-World War II. Nuclear power, computer controls, and other developments helped fine-tune the grid’s effectiveness and operability. Although today’s technology has flown light-years into the future, the national power grid has not kept up pace with modernization. The grid has evolved little over the past fifty years.” (Assignment point)

2. SMART GRID TECHNOLOGIES

Key components and architecture of smart grids

“A smart grid system has a highly distributed and hierarchical network architecture. It utilizes intelligent sensing devices to collect information regarding each grid component to make an informed decision regarding its operation.” (Stellaris)

“The main components of a Smart Grid (Figure 1) are electric power generators, electric power substations, transmission and distribution lines, controllers, smart meters, collector nodes, and distribution and transmission control centres” (Mavridou and Papa)

Infrastructure for Advanced Metering (AMI)

a. “Advanced metering infrastructure (AMI) is an integrated, fixed-network system that enables two-way communication between utilities and customers. The system collects, stores, analyzes and presents energy usage data, providing utility companies with the ability to monitor electricity, gas and water usage in real-time.” (IBM). It also helps in identifying power outages and helps to restore the service. This is especially helpful as it aids in energy conservation and cost reduction for major companies.

b. Systems for Distribution Management (DMS)

“A distribution management system is modern software that helps monitor, control, and optimise electrical distribution networks. In addition, it helps in improving grid readability, enhancing efficiency, and reducing downtime. As a result, it boosts the overall productivity of the process.” (Schneider Electric)

c. Energy Management Systems (EMS)

"An energy management system (EMS) is a set of tools combining software and hardware that optimally distributes energy flows between connected distributed energy resources (DERs). Companies use energy management systems to optimize the generation, storage and/or consumption of electricity to lower both costs and emissions and stabilize the power grid." (grids)

2.1 The function of ICT (information and communication technology) Smart Sensors and IOT (Internet of Things)

By using Internet of Things (IoT) devices, smart grids will be able to assimilate renewable energy by depending on Information and Communication Technology (ICT), as well as smart sensors. In this regard, the networked systems collect information from different points within the grid including power generation sources, substations and end-user devices before transmitting it across communication networks. This advanced analytics is in charge of data analysis whose outcomes are used for real-time monitoring of grid operations and control through automation. Furthermore, consumers can access this information online and they can also participate in demand response programs with a guarantee that there is no cyber security breach.

These IoT devices work alongside smart sensors that provide accurate updates on various issues about electricity delivery systems among them voltage fluctuations, current strength or even power quality at a given time. These strategically located sensors communicate the collected data via a central ICT system or cloud-based platforms. For example, local handling of data allows immediate response to critical situations or functions such as load balancing and voltage regulation for efficient management of electrical power distribution systems. Also played vital roles for predictive maintenance activities associated with equipment condition and signal the need for repairs before failures occur.

3. RENEWABLE ENERGY SOURCES

Types of renewable energy sources (solar, wind, hydro, biomass, geothermal). Characteristics and benefits of each type. Some types of renewable energy sources are solar energy, wind energy, hydro energy, biomass energy and geothermal energy.

Solar Energy- It is the energy supplied by the sun. The energy is collected mainly through cells called photovoltaic cells. The photovoltaic cells absorb some photons which trigger the release of charges and hence generate electricity.

Its benefits are-

It is available in large quantities for a long period.

It is everywhere.

It is very cost-effective

Wind Energy: It is the energy generated by wind through the use of windmills. In windmills the wind turbine rotates with the help of wind and the kinetic energy is converted to electrical energy through the generator.

It can be an excellent source of power in remote areas

It is a great source of power for farming and other local uses

Its operating costs are low.

Hydropower: It is the energy obtained by water through water turbines. When water enters a turbine it causes it to rotate and make kinetic energy which is converted to electrical energy through a generator.

Some advantages are:

It reduces the risk of floods in areas

It increases the stability of power grids

Geothermal energy: It is the energy obtained from the heat within the earth through geothermal power plants."Geothermal power plants draw fluids from underground reservoirs to the surface to produce heated material. This steam or hot liquid then drives turbines that generate electricity before it is reinjected back into the reservoir."(Department of Energy)

Some of its advantages are-

It provides a steady, baseload power source

It requires a small amount of space

The amount of maintenance required is low.

It is very environmentally friendly.

3.1 Current status and trends in renewable energy adoption

Solar energy is seeing a huge amount of growth mainly due to the lower cost of photovoltaic panels while at the same time, the efficiency is increasing." Solar PV generation increased by a record 270 TWh (up 26%) in 2022, reaching almost 1 300 TWh. It demonstrated the largest absolute generation growth of all renewable technologies in 2022, surpassing wind for the first time in history" (International Energy Agency)

"The global wind industry installed a record 117GW of new capacity in 2023, making it the best year ever for new wind energy, finds this year's Global Wind Report from the Global Wind Energy Council." (Global Wind Energy Council)

"The report highlights increasing momentum on the growth of wind energy worldwide:

Total installations of 117GW in 2023 represent a 50% year-on-year increase from 2022

2023 was a year of continued global growth – 54 countries representing all continents built new wind power

GWEC has revised its 2024-2030 growth forecast (1210GW) upwards by 10%, in response to the establishment of national industrial policies in major economies, gathering momentum in offshore wind and promising growth among emerging markets and developing economies" (Global Wind Energy Council)

3.2 Future trends

"In 2024, wind and solar PV together generate more electricity than hydropower.

In 2025, renewables surpass coal to become the largest source of electricity generation.

Wind and solar PV each surpass nuclear electricity generation in 2025 and 2026 respectively.

In 2028, renewable energy sources account for over 42% of global electricity generation, with the share of wind and solar PV doubling to 25%." (International Energy Agency) "Historic investment in renewables will come into fuller view in 2024.

Solar and storage deployments are soaring, and clean hydrogen is teed up for takeoff, while offshore wind is navigating rough waters. Transmission is the key obstacle to tackle" (Deloitte)

4. INTEGRATION OF RENEWABLE ENERGY WITH SMART GRIDS

4.1 Challenges in integrating renewable energy into traditional grids

There are some challenges linked to the integration of renewable energy sources into smart grids.
Intermittency and variability
Renewable energy sources like solar and wind are very uneven and variable. For example- sunlight depends on many factors like weather conditions and time of the day and wind power depends on wind speed. Now some of these conditions might not be met at some times of the day leading to instability.
Traditional power grids used nowadays are designed for consistent and controllable energy sources like coal, natural gas, or nuclear. However, the variable nature of renewable energy sources used can lead to fluctuations in power supply to the grid, making it challenging to maintain the much-required grid stability.
Demand-supply mismatch: There is also a high possibility of a mismatch between demand and supply. For instance, the availability of sunlight, which is used for the generation of solar power, is highest in the afternoon, while the need may be high in the evening. Such conditions make storage or alternative power sources necessary.
Inertia Reduction: The power plants currently in use are traditional meaning they use non-renewable materials like coal and gas. The problem with integrating renewable resources is that the materials like coal and gas provide inertia to the grid. The inertia produced in turn stabilizes the grid. Now, if renewable resources were to be integrated, especially wind and solar, they would not contribute the same level of inertia and this would result in the grid becoming unstable.
Localized Voltage Issues: The generation of renewable energy can cause violent changes in voltage, especially when connected at the ground level. Now, these changes can be highly problematic for the grid by destabilizing it. The generation can, thus cause problems like voltage sags or voltage swells. These sags and swells can cause equipment, machinery failure, reset and other problems.
Reactive Power Management:
With maintaining voltage stability also comes the responsibility of managing reactive power. The traditional power plants used currently, contribute to reactive power, but the renewable sources might not necessarily provide the same support. Thus, making additional equipment or grid management strategies necessary.
Solutions and technologies for integration
Demand response and load management

5. ADDRESSING INTERMITTENCY AND VARIABILITY

Demand response (DR) is key in adjusting the grid in response to unstable solar and wind. DR gives control to consumers thereby adjusting demand on supply conditions. For example, these consumers can decide to shift or lower their energy use when renewable energy generation is low; hence balancing the grid and reducing the need for fossil fuel generation as backup.
Load Shifting: In this regard, load management strategies such as time-of-use pricing may encourage customers to use electricity when renewable energies are more abundant. This not only makes the demand curve smooth but also ensures efficient use of renewable energy, which reduces waste too
Distributed generation and microgrids
Energy storage systems (batteries, pumped hydro, etc.)
Due to the variability of renewable sources, some kind of energy storage systems are needed. The most significant of them are batteries and pumped hydro.
Batteries store the excess energy generated by renewable sources like solar and wind when production is higher than the demand. The batteries store the energy through chemical reactions and convert the electrical energy to chemical energy and store it in the electrodes. When the demand is high, they discharge and convert the chemical energy back to electrical and supply it to the grid. For ex- for solar power, the energy is stored during the midday when the supply of sunlight is the highest and the excess power is supplied to the grid when the need for energy is needed. This stored energy can be released during periods of low renewable generation, ensuring a consistent power supply. The need for backup fossil fuel generators is also decreased by using batteries due to the above characteristics. The most common batteries used in smart grids include lithium-ion, lead-acid, and flow batteries. (Prysmian)
Pumped Hydro Storage or PHS is a type of storage which is similar in strategy to batteries i.e. the energy is stored at a time of low demand, and high storage and supplied consistently as per the needs. However, it has a completely different mechanism. It involves using this surplus electricity to pump water from a lower reservoir to a higher one. This makes the water store gravitational potential energy. When the energy is needed the water which contains P.E is allowed to flow to the lower reservoir through turbines which convert gravitational P.E to electrical energy and the energy is supplied to the power grid. It is mostly used for wind and solar energies. (Department of Energy)
Forecasting and predictive analytics play a crucial role in managing smart grids.
Data Collection: Real-time data such as weather forecasts, energy consumption patterns, and grid performance metrics are gathered from various sources.
Modelling and Decision Making: It involves the use of Advanced algorithms, such as machine learning and statistical models, which are used to analyze historical and real-time data to predict future energy demand and renewable energy generation. This is helpful as it decreases the chances of failure of the power grid thus increasing stability.
Applications: For example - Forecasting predicts solar and wind generation, while predictive analytics helps manage energy loads, reduce costs, and improve grid reliability. For example, predicting when a cloudy day might reduce solar output allows the grid to preemptively switch to stored energy sources.

6.BENEFITS AND IMPACTS

6.1 Environmental and economic benefits

There are many Environmental benefits. Firstly, it will lead to much less greenhouse gas emissions, since renewable sources like solar, wind geothermal, etc. Produce little to no greenhouse gases. It also would decrease Air and Water Pollution., Unlike coal and natural gas plants, renewable energy systems do not emit pollutants that add to smog, acid rain, and water contamination. It als o encourages the conservation of natural resources since the renewable resources used in the smart grid, as the name suggests, are renewable whereas the traditional grids involve the use of finite sources like coal, petroleum, etc. Which once finished take millions of years to restore. They also reduce land use since many don't require much land but some do, for example - solar energy which requires panels can be acquired in ways that minimize land usage.

There are also large amounts of economic benefits. Firstly, it will lead to job creation i.e. create employment opportunities in the renewable sector. It will decrease the dependence of countries on imported fossil fuels which can stabilize the energy prices of the country. The long-term operational costs are also lower than traditional grids. It can diversify the economies of countries by introducing new fields of industries and technologies, in turn, reducing economic vulnerability and increasing resilience against market fluctuations.

6.2 Social and policy implications

Energy equity and access: The integration of renewable energy into smart grids has at least one advantage, namely a more decentralized power generation system that makes it easier to reach out to remote and underserved communities in terms of energy. The upshot may be the reduction of energy poverty by offering cheap and dependable electrical energy to areas which could have been inadequately served by conventional grids. Renewable sources are dispersed enough for the community to generate its power, with any excess being sold back into the grid. Like this, it can tip the scales from large utility companies towards local communities and individuals thus enhancing the fairness in the distribution of energy.

Cost Implications: This will need to entail substantial costs to be transferred to consumers. There is a danger of these costs being pushed down to consumers, especially the low-income ones. This should not happen as it would lead to unfair distribution among populations with different capabilities.

Access to Technology: All communities must have access to smart grid technologies, particularly those that are marginalized. These include the digital literacies for energy efficiency management, smart meters, and storage systems of energy.

6.3 Policy frameworks and regulatory support

Regulatory Reforms: The integration of renewable energy into smart grids requires substantial regulatory reform. This includes updating grid codes, market structures, and tariff designs to accommodate intermittent renewable sources and distributed generation.

Incentives for Renewable Integration: Governments need to provide incentives for both consumers and producers to invest in renewable energy and smart grid technologies. This could include tax credits, subsidies, or feed-in tariffs that make renewable energy generation financially attractive.

Ensuring Grid Stability: Policies must address the technical challenges of integrating variable renewable energy sources into the grid. This includes supporting the development of energy storage solutions, demand response programs, and the implementation of advanced grid management technologies.

Standardization and Interoperability: To fully realize the potential of smart grids, policies should encourage the development of standards that ensure interoperability between different technologies and systems. This will help create a seamless, efficient energy system that can integrate diverse renewable energy sources.

Environmental and Social Impact Assessments: Policies should require comprehensive impact assessments to ensure that the deployment of smart grids and renewable energy sources does not negatively impact communities or ecosystems. These assessments should include considerations of land use, biodiversity, and social equity.

Global Collaboration: Renewable energy and smart grids are global issues, requiring international cooperation on policy frameworks, research and development, and the sharing of best practices. Collaboration can accelerate the transition to a more sustainable and equitable energy system worldwide.

7. CONCLUSION

The integration of renewable energy into smart grids is a huge change in the energy sector concerning the current conditions. The grids which are currently used (also known as the conventional grids) run on fossil fuels and are not sufficient for use mainly due to their poor reliability and sustainability. This means they add to and worsen the environmental problems while being less reliable. This is where we need smart grids. These smart grids not only enable the integration of renewable energy sources and make the grids more sustainable, but they also solve the problem of reliability through their sophisticated architecture.

This particular research study has not only depicted the characteristics of smart grids, but has also emphasized the advantages of smart grids in the present energy systems in terms of efficiency, stability, and environmental protection. The fluctuation of renewable sources of energy can be controlled with the help of new technologies such as monitoring systems, automatic control and two-way communication. A quick proposition towards such a purpose shall be to an imperative source of energy and optimise the source and demand of energy. In this way less energy is lost, and uninhibited gasses are released.

Also, key measures enhancing the current smart grids and preparing them for future changes include the creation and introduction of demand response, energy storage, and distribution generation systems. These risks can be alleviated very well by such innovations including designing and installing intermittency of renewable energy for smooth operation and not crashing the grid where interruptions could happen. From this point, there is thermal dissipation of excess heat which could otherwise be destructive to the environment and intelligent energy systems in integration besides that governance inclusion is so critical. Advancement in renewable energy utilization will require the possession of smart grids which will for example enable bulk storage of energy.

In conclusion, the integration of renewable resources has to take place with collaboration between many sectors, extensive research and development and inclusion of policymakers, industry leaders and communities. Therefore, it is not just a technical challenge but also a social one.

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